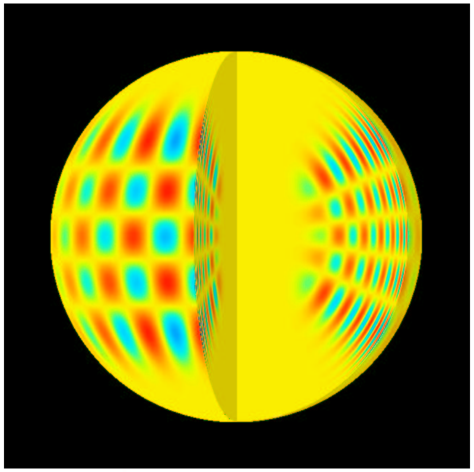
HELIOSEISMOLOGY (I)

acoustic mode
in the Sun
(p mode
n=14, l -20)



full-disk
Dopplergram

velocity (km/s)

STRUCTURE OF THE SUN

- The *Sun* is the only star for which we can *measure* internal properties → test of stellar structure theory
- *Composition* (heavy elements) from *meteorites*
- *Density, internal rotation* from *helioseismology*
- *Central conditions* from *neutrinos*

HELIOSEISMOLOGY

- The Sun acts as a *resonant cavity, oscillating* in millions of (acoustic, gravity) modes (like a bell)

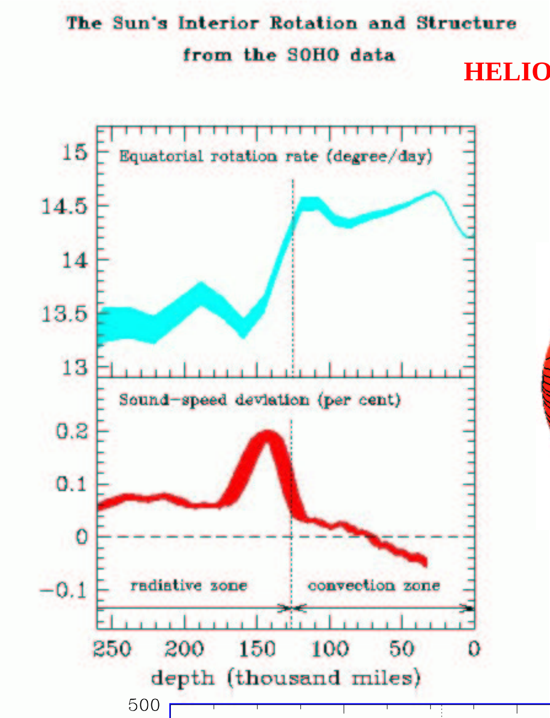
→ can be used to reconstruct the internal density structure (like earthquakes on Earth)

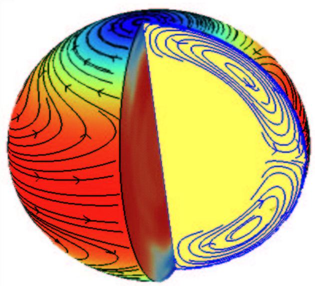
- oscillation modes are *excited* by *convective eddies*
- *periods* of typical modes: *1.5 min to 20 min*
- *velocity amplitudes:* $\sim 0.1\,m/s$
- need to measure *Doppler shifts* in spectral lines relative to their width to an accuracy of $1{:}10^6$
  - ▷ possible with good spectrometers and long integration times (to average out noise)

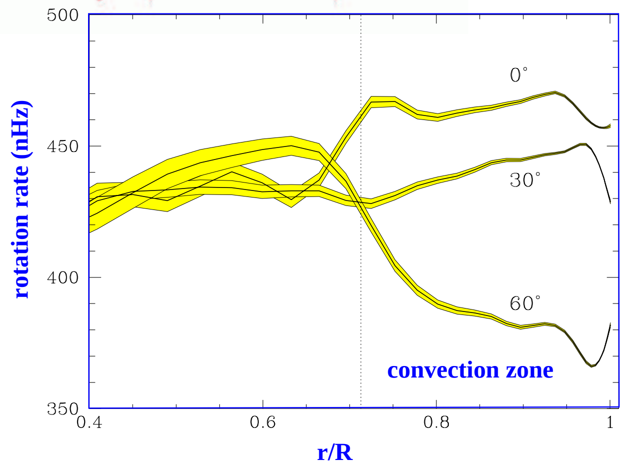
Results

- *density* structure, *sound speed*
- depth of outer *convective zone:* $\sim 0.28\,\mathrm{R}_\odot$
- *rotation* in the core is *slow* (almost like a solid-body) → the core must have been spun-down with the envelope (efficient core–envelope coupling)

HELIOSEISMOLOGY (II)







SOLAR NEUTRINOS

- *Neutrinos,* generated in solar core, *escape* from the Sun and carry away $2-6\,\%$ of the energy released in H-burning reactions
- they can be observed in *underground experiments* $\rightarrow$ *direct probe of the solar core*
- neutrino-emitting reactions (in the pp chains)

$$
\begin{aligned}
{}^1\mathrm{H} + {}^1\mathrm{H} &\rightarrow {}^2\mathrm{D} + \mathrm{e}^+ + \nu \qquad \mathrm{E}_\nu^{\max} = 0.42\,\mathrm{Mev} \\
{}^7\mathrm{Be} + \mathrm{e}^- &\rightarrow {}^7\mathrm{Li} + \nu \qquad \mathrm{E}_\nu^{\max} = 0.86\,\mathrm{Mev} \\
{}^8\mathrm{B} &\rightarrow {}^8\mathrm{Be} + \mathrm{e}^+ + \nu \qquad \mathrm{E}_\nu^{\max} = 14.0\,\mathrm{Mev}
\end{aligned}
$$

- The *Davis experiment* (starting around 1970) has shown that the neutrino flux is about a factor of 3 lower than predicted $\rightarrow$ *the solar neutrino problem*

The Homestake experiment (Davis)

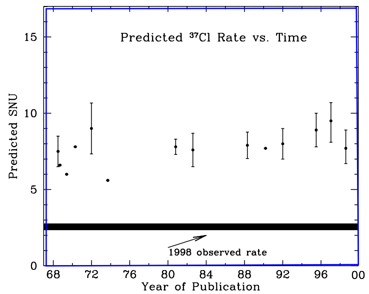
- *neutrino detector:* underground tank filled with 600 tons of Chlorine ($C_2\,Cl_4$: dry-cleaning fluid)
- some neutrinos react with Cl

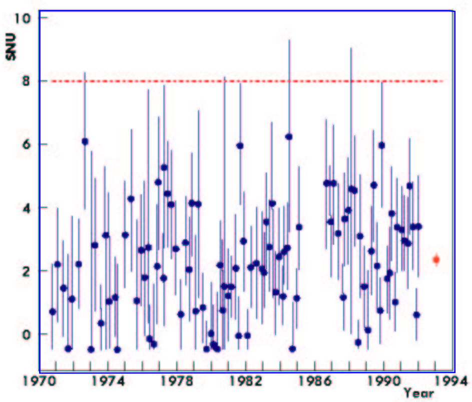
  $\nu_\mathrm{e} + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^- - 0.81\,\mathrm{Mev}$
- rate of absorption $\sim 3 \times 10^{-35}\,\mathrm{s}^{-1}$ per ^{37}Cl atom
- every 2 months *each* ^{37}*Ar atom is filtered out* of the tank (expected number: 54; observed number: 17)
- *caveats*
  - ▷ difficult experiment, only a tiny number of the neutrinos can be detected
  - ▷ the experiment is only sensitive to the most energetic neutrinos in the ^{8}B reaction (only minor reaction in the Sun)

The Davis Neutrino Experiment

Homestake Mine
(with Cl tank)

Model Predictions





Results

Proposed Solutions to the Solar Neutrino Problem

- dozens of solutions have been proposed

1) *Astrophysical solutions*

▷ require a *reduction in central temperature* of about 5 % (standard model: 15.6×10^6 K)

▷ can be achieved if the solar core is mixed (due to convection, rotational mixing, etc.)

▷ if there are *no nuclear reactions in the centre* (inert core: e.g. central black hole, iron core, degenerate core)

▷ if there are *additional energy transport* mechanisms (e.g. by WIMPS = weakly interacting particles)

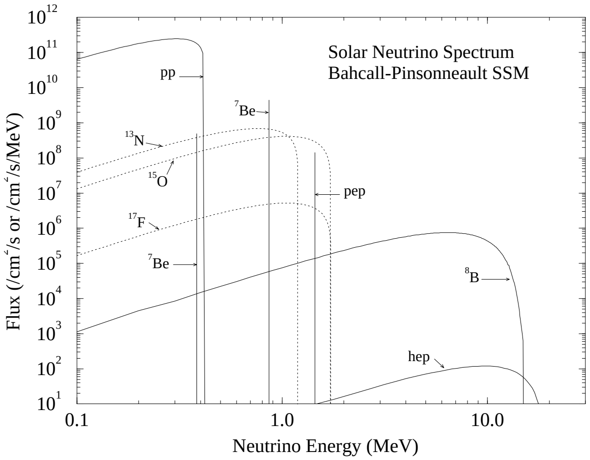
▷ most of these astrophysical solutions also change the density structure in the Sun → can now be *ruled out by helioseismology*

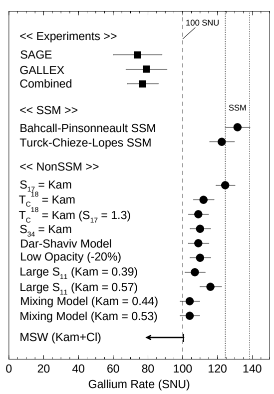
2) *Nuclear physics*

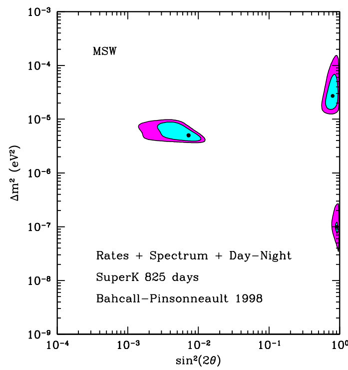
▷ errors in *nuclear cross sections* (cross sections sometimes need to be revised by factors up to ~ 100)

▷ improved experiments have *confirmed the nuclear cross sections* for the key nuclear reactions

Solar Neutrinos







3) *Particle physics*

- ▷ all neutrinos generated in the Sun are *electron neutrinos*
- ▷ if neutrinos have a *small mass* (actually mass differences), neutrinos may change type on their path between the centre of the Sun and Earth: *neutrino oscillations,* i.e. change from electron neutrino to μ or τ neutrinos, and then cannot be detected by the Davis experiment
- ▷ *vacuum oscillations:* occur in vacuum
- ▷ *matter oscillations (MSW [Mikheyev-Smirnov--Wolfenstein] effect):* occur only in matter (i.e. as neutrinos pass through the Sun)

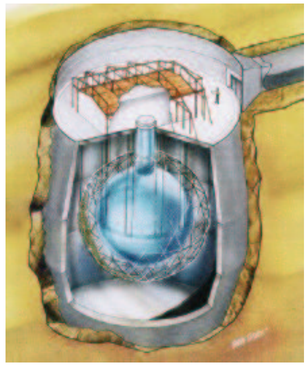
RECENT EXPERIMENTS

- resolution of the neutrino puzzle requires more sensitive detectors that can also detect neutrinos from the main pp-reaction

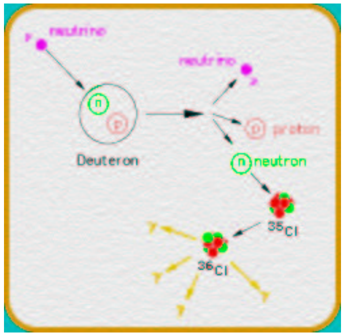
1) *The Kamiokande experiment*
(also super-Kamiokande)

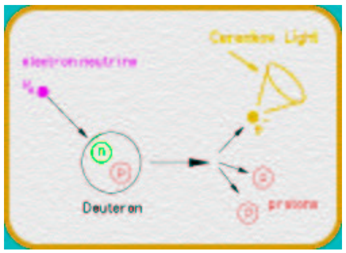
- ▷ uses 3000 tons of ultra-pure water (680 tons active medium) for
$\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$ (inelastic scattering)
- ▷ about six times more likely for ν_e than ν_μ and ν_τ
- ▷ *observed flux:* half the predicted flux (energy dependence of neutrino interactions?)

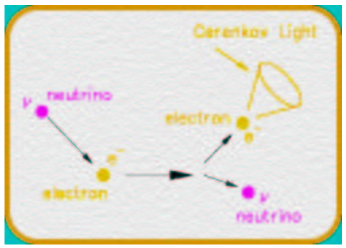
The Sudbury Neutrino Observatory

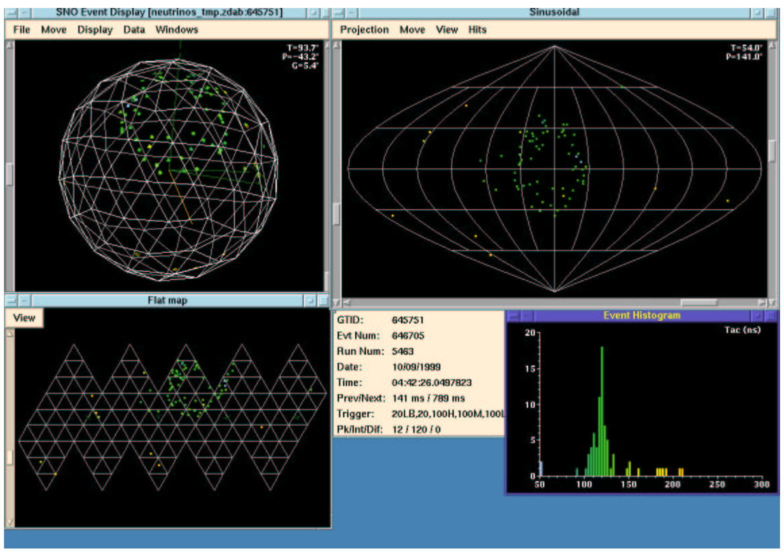


1000 tons of heavy water









2) *The Gallium experiments* (GALLEX, SAGE)

- ▷ uses Gallium to measure low-energy *pp neutrinos* directly
  $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- - 0.23\,\mathrm{Mev}$
- ▷ *results:* about 80 ± 10 SNU vs. predicted 132 ± 7 SNU (1 SNU: 10^{-36} interactions per target atom/s)

3) *The Sudbury Neutrino Observatory (SNO)*

- ▷ located in a deep mine (2070 m underground)
- ▷ 1000 tons of pure, *heavy water* (D_2O)
- ▷ in acrylic plastic vessel with 9456 light sensors/photomultiplier tubes
- ▷ detect *Cerenkov radiation* of electrons and photons from weak interactions and neutrino-electron scattering
- ▷ *results (June 2001): confirmation of neutrino oscillations (MSW effect)?*